Chapter 7
The Last Hero-Inventor: A Theory of Innovation?

Abstract In our last iconoclastic example of the genius-inventor we construct a social network for Willis Carrier and the beginnings of air conditioning technology. In a summary of exponential knowledge growth in other technologies, we draw the conclusion that human patterns of innovation have been similar across two centuries but that the time scale for explosive growth has been decreasing dramatically. We also review the elements for constructing social networks in the history of technology and speculate on models for innovation.

From clocks in the eighteenth century to chaos theory in the twentieth century we have charted the connections between history's knighted hero-inventors and geniuses and their sometimes hidden networks through which they found their epiphany moments. Characteristic of these examples has been evidence for exponential increases in events and product acceptance accompanied by an increase in the historical innovation nodes and links in the network. We have provided evidence that the statistical nature of these networks has characteristics of contemporary social networks and the World-Wide Web. Do a few examples make a universal theory? Of course not. As an experimentalist the author was led from one case study to the next in search of exceptions. Perhaps one exception is the ballooning technology of the late eighteenth to the early twentieth century, a case of linear progress ending in the failure of Count Zepplin's dirigible.

In the twentieth century, the technology of magnetic levitation of trains was another example of intense public interest and engineering excitement in the 1970s and 1980s, only to falter as conventional rail closed the speed gap in the 1990s. In physics there is the case of cold fusion in the 1990s. It is not the claim that only successful technical and scientific innovations arise from complex historical networks, but that both enduring and fading innovations arise from social networks. Whether these innovations become embedded in modern society depends on many factors independent of the inherent nature of the innovation or invention. Our point is that innovations and inventions by their nature demand a societal network to come before

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the stage of history. Economic, political and societal factors cast the ultimate votes for acceptance.

Sometimes the failed technology, such as steam piston engines, enables a newer, more enduring one. It set the stage for the Industrial Revolution only to be replaced by the steam turbine used in power plants today and the internal combustion engine. Was the steam piston engine a failure? Most historians would argue not—it was a necessary step in the evolution of steam power and energy producing machines. Similarly with the decline of vacuum tube technology and analog electronics, only to be replaced by transistor electronics and eventually silicon-embedded chip circuitry and digital electronics. Could silicon-based electrical products have leap-frogged de Forest's triode tube and Armstrong's superheterodyne circuits? Evolution in biology took many branched paths and technical and scientific evolution is probably no different.

Before becoming too pontifical in this summary chapter, we look at one more example of a technology that was successful a century ago, survived and changed the demographics of living patterns on Earth, and threatens to be a key factor in solving the threats to global climate change. This technology is air-conditioning and the heir apparent to the hero-inventor in Willis Carrier, another Cornell University mechanical engineering graduate of 1902.

Fig. 7.1 Willis Carrier c. 1915, cornell class of 1902, mechanical engineering. Introduced humidity control to the heating and cooling of buildings

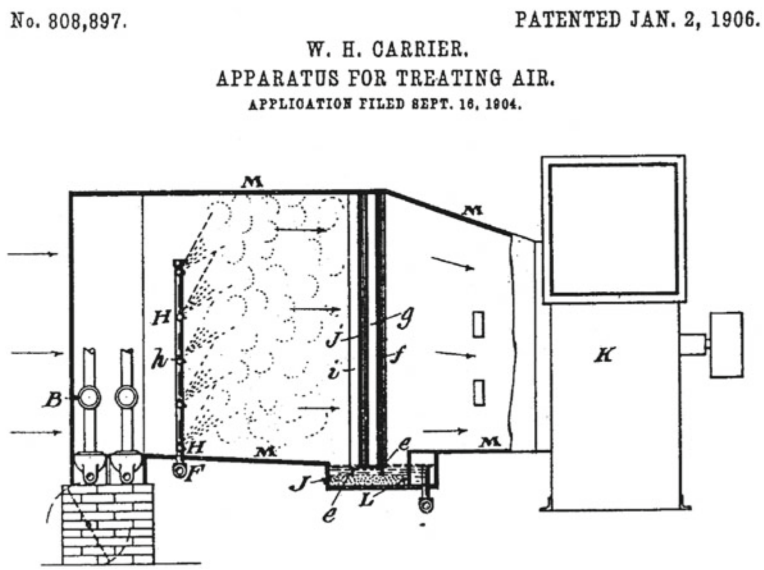

Fig. 7.2 Willis Carrier first air conditioning patent 1906, No. 808897

7.1 Willis H. Carrier and the Persistence of the Genius Myth

In a recent book on innovation by Johnson (2010), *Where Good Ideas Come From*, Johnson makes a very strong case for the importance of societal parameters for the creation and diffusion of innovative ideas, including social networks. However in his last chapter Johnson tries to demonstrate that even though most ideas are evolutionary and collaborative, there are a few that come from the individual genius. His principal example is Willis Carrier [1876–1950], Fig. 7.1, and the invention of air conditioning (See patent front page in Fig. 7.2). There was no intent to study this class of inventions because the ancillary subject of thermodynamics is broad and deep with many important players spread out over a century or more. But the challenge was there to see if Carrier had created modern air conditioning machines in the absence of a social network.

The principal nodes in air conditioning technology and related thermodynamic science are listed below.

Principal Nodes in Applied Thermodynamics Network

Sadi Carnot [1796–1832] French engineer who proposed limits to heat engines.
Rudolf Clausius [1822–1888] German physicist. Put Carnot's ideas into formal theory. Defined the concept of entropy.
William F. Rankine [1820–1872] Scottish physicist and engineer. Described the basic laws of thermodynamics.

Lord Kelvin [1824–1907] British engineer and physicist. Contributed to science of electricity and thermodynamics.

Carl von Linde [1842–1934] German engineer who pioneered in refrigeration technology. Teachers at Swiss ETH were Clausius and Reuleaux.

Robert H. Thurston [1839–1903] American mechanical engineer, expert on the steam engine, and professor at Stevens Institute and Cornell University.

Alfred R. Wolff nineteenth century. American engineer who introduced heating and cooling of buildings.

Rolla C. Carpenter [1852–1919] American engineer and professor at Cornell University. President of the American Society of Heating and Ventilating Engineers 1898.

Willis H. Carrier [1876–1950] American engineer who introduced humidity control the ventilation and heating of buildings. Founder of Carrier Corp. Graduate of Cornell University.

Wendt Brothers Buffalo NY manufacturers of centrifugal fans and air-conditioning equipment in early twentieth century.

7.1.1 Air-Conditioning Machines Social Network

In Fig. 7.3 is a star network centered around Willis Carrier and gleaned from his biographies and web-based sources (Ingels 1952; Wampler 1989). Many of the important nodes in thermodynamics are not shown in this network.

Description of Carrier Network Links

Willis Carrier grew up on a farm in northwestern New York State near Buffalo and won a state scholarship to attend the engineering college at Cornell University, known as the Sibley College of Mechanical Engineering and Mechanics Arts in Ithaca New York. After graduation in 1902, he was hired by the Buffalo Forge Company which produced pumps and centrifugal ventilation equipment. At the same time the Sackett-Wilhelm Lithography Company in Brooklyn NY, wrote to Buffalo Forge to see if they could purchase equipment that would control the humidity in their factory because their four-color printing process was sensitive to temperature and humidity. Fortuitously Willis Carrier was given the job and he designed a system that would control both variables. This innovation evolved into a patent (see Fig. 7.2) and several years later Carrier and other engineers left to form the Carrier Engineering Corporation that today is part of United Technologies Corporation. This move led to development of a new consumer technology that in turn changed the economic and demographic history of the Southern US, especially for the state of Florida. This story of young genius and entrepreneurship can be found repeated in many hard and soft media formats.

However, this story is much more complicated. Not to take anything away from Carrier's drive and accomplishments, we can't ignore that in 1902, he had just attended 4 years of an intensive engineering program in mechanical engineering with a concentration in electrical applications. The Director of the Sibley College at

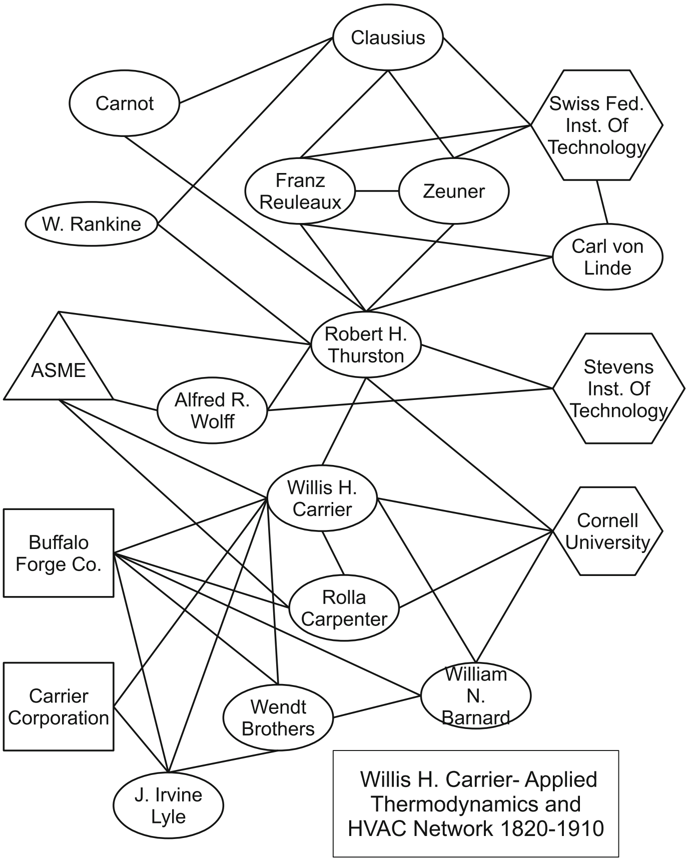

Fig. 7.3 Partial applied thermodynamics network centered around Willis H. Carrier and air conditioning and refrigeration machines

Cornell was Professor Robert H. Thurston, one of the most renowned authorities in applied thermodynamics. He was also one of the founding members as well as the first president of the American Society of Mechanical Engineers. Thurston had spent 14 years at Stevens Tech in NJ near New York City and helped establish an more academically and science-based engineering program there before coming upstate to Ithaca New York to take over the Cornell Sibley College in 1885.

All students at the Cornell Sibley College had to take Thurston's course on the steam engine that, according to the syllabus, contained a good dose of applied thermodynamics. Students also had to take a course in mechanical engineering laboratory taught by Professor Rolla C Carpenter that included experiments in applied thermodynamics including refrigeration. As it turned out, Carpenter was the author of two books on heating and ventilation of buildings that also contained material on cooling of buildings (Carpenter 1893).

Thus the farm boy Willis Carrier was immersed in a curriculum that taught new engineers to use science and math-based design methods. If there was no basic scientific theory to underpin the design, they were taught to construct experimental tables with data that would provide guidelines for design choices such as size, shape, materials etc. This is what Carrier did when he first came to Buffalo Forge. He convinced the owners, the Wendt brothers, that their designs were not based on scientific and experimental principles. Carrier was given charge of a department that would develop new data and charts to allow Buffalo Forge to produce efficient machines that would increase the Wendt brothers' profits. It was out of this new laboratory that Carrier developed his air conditioning system for Sackett-Wilhelm Lithography.

At the turn of the century, the principal nodes in the environmental control of building spaces were Carl von Linde in Munich, Alfred R. Wolff in the US and Willis Carrier. As we have seen in the early aviation network, Robert Thurston played the role of a secondary but enhancing node in the air conditioning machine network. Thurston had written a history of the steam engine that included a survey of the evolution of the subject of heat energy and thermodynamics. He had also written a popular book on the principles and applications of heat energy as well as translated the work of Sadi Carnot into English, one of the discoverers of the second law of thermodynamics (Thurston 1890).

One tool for applying thermodynamics was the use of a "thermodynamic cycle", and it was common knowledge at that time that design of machines to create cold or refrigeration could be understood in the same way one designed a steam engine. This knowledge would surely have been transmitted to students in Thurston's courses in the Sibley College.

Another player in refrigeration at the time was von Linde in Germany who had studied with Gustav Zeuner, Rudolf Clausius and Franz Reuleaux in ETH in Zurich from 1861–1864. Reuleaux was a secondary node in the internal combustion engine network as well as in the aviation network with his help of Lillienthal in Berlin. Reuleaux also helped von Linde get his first job. Rudolf Clausius along with William Rankine was one of the principal developers of thermodynamic theory. Gustav Zeuner went to the Technical University of Dresden and was one of the founders of technical thermodynamics. After Zurich, von Linde became a professor at the Technische Hochschule of Munich and developed machines to produce extreme cold which could liquefy air and other gases. In 1879, he left the university to start his own company, Linde AG, designing refrigeration machines for breweries. Von Linde's accomplishments cannot ignore his connections to the Technical University at Zurich, Zeuner and Clausius. In the same way Carrier's invention of a cooling and humidity control system cannot be viewed in isolation from his scientific and technical education at Cornell University.

To further complete the social network, shown in Fig. 7.3, we have the important node of Alfred R. Wolff who was a graduate of Stevens Institute of Technology when Thurston was a professor there. Wolff is credited with producing cooling systems for several important buildings in New York City before and around the time that

Carrier got the Sacket-Wilhelm Lithography job. Woolf also was a Charter member of the ASME of which Thurston was first president.

Another network link is that between Professor Carpenter and Buffalo Forge. Carpenter had written a book on ventilation in buildings around 1891 (Carpenter 1891, 1902). The back of one edition of the book contains advertisements and includes a full page ad from Buffalo Forge Co. Carpenter was also a consultant to many companies but we have not been able to make a stronger link between him and BFC. However a biography of Carrier, notes that BFC visited Ithaca to recruit Cornell students and that is how Carrier got a job. One may speculate that either Carpenter or Thurston knew one of the principles of Buffalo Forge.

Another Cornell node was William N. Barnard, an assistant professor during Carrier's studies at Cornell (Barnard et al. 1912, 1915). Barnard wrote a popular book in 1912, *Heat Power Engineering*, with two other faculty members. In the biography by Ingels (1952) mention is made of how Professor Barnard visited Buffalo Forge in 1902 to see how Cornell graduates such as Willis Carrier were doing. Thus Carrier continued to have contact with Cornell faculty after he went to Buffalo.

One of the hallmarks of the genius myth is the 'epiphany story' often told by the hero-inventor years after the event. In the example of Willis Carrier, this story appears in several biographical essays and books in which the key idea of dew point control came to him while he was on a foggy rail platform in Pittsburgh waiting for a train. This "genius myth" received official sanction in a millennium book on innovation in the twentieth century by the National Academy of Engineering in 2000. But the idea that Carrier invented the psychometric chart without other influences and single-handedly invented air-conditioning does not agree with the history of heat energy.

Oddly when the author was researching this network, a colleague at Cornell mentioned that he used this story in a motivational lecture to new students, to show that one of them might become a future Carrier and create of a new industry. So the genius myth still plays its role in educating the next generation of engineers and scientists.

As further evidence that air-conditioning technology followed a path similar to that of internal combustion engines and radios, we plot the growth in air-conditioning related events in Fig. 7.4a that shows again the exponential growth in a knowledge base. If we plot the same data on a logarithmic scale (Fig. 7.4b), we can see a straight-line region, indicating an exponential growth period from around 1840–1910. This milestone chart is based in part on a biography of Carrier edited by the Carrier Corp that he founded. This chart shows that Willis Carrier left Cornell in 1902 for his job with Buffalo Forge at a time when he was immersed in an avalanche of knowledge associated with the heating, cooling and ventilation of enclosed spaces using the ideas of thermodynamics.

One idea that emerges from this study is that patents and copyrights rarely slow the progress of human society in embracing some new idea or device. Sometimes it is not necessary for an outsider to gain direct knowledge of a trade secret. It is possible that the 'fact' that someone has accomplished some feat or created some new process is enough to motivate an outsider to try and duplicate, improve or optimize the invention or innovation. Imitation is an important feature of human learning.

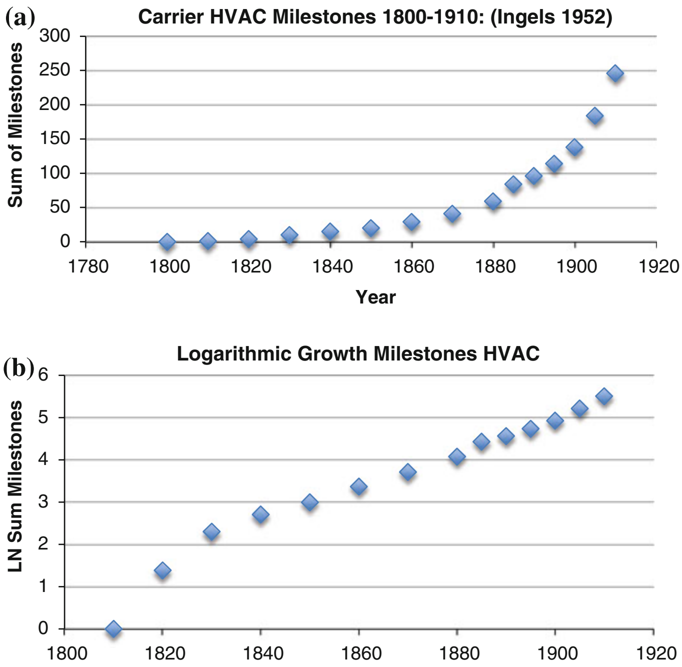

Fig. 7.4 **a** Graph of the sum of events associated with the thermodynamics and its application to heating, cooling and ventilation of enclosed spaces. **b** *Vertical scale* is the logarithm of the data in **a**. The *straight-line* region indicates an time period of exponential growth in knowledge in applied thermodynamics and HCAC (*Source*, Ingels 1952)

In the preceding chapters we have presented data on the exponential rise of innovation in a half dozen areas spurred on by the growth of social networks. The *rising tide of knowledge* in many technical and scientific areas is sometimes all that is necessary for someone to break out of the pack and promote new ideas, inventions and methodologies.

7.2 The End of the Genius-Inventor and the Rise of a Theory of Innovation

From the histories and data in Chaps. 1–6, we have seen common patterns in the evolution of invention and innovation in disparate areas, from steam engines to radios. Characteristic of all the technologies and scientific ideas we have studied is the simultaneous appearance of a network of individuals and institutions that grows exponentially as the milestones of innovation progress increase. We have used the analogy of an avalanche of sand in which small movements of particles continue to generate a distribution of smaller avalanches. This self-generation of motion has been

called different names such as "*self-organized criticality*" or SOC by Per Bak (1996) and "strategic exchange in social systems" by G. D. Snooks (1998). Computational economists have used the term "agent-based modeling" or ABM as in e.g. Ball (2004) in his book *Critical Mass-How One Thing Leads to Another*.

A summary of the growth curves for eight of the different technologies and scientific theories discussed in this book are shown in Fig. 7.5. There is nothing to suggest that similar patterns of innovation advancement would not be seen in other technologies such as railroads, telephones, transistors or lasers. The only feature we can discern between steam engines and radios or between radio electronics and chaos theory is the decrease in the time scale to reach the peak of activity. If we plot the logarithm of the growth measure versus time, we obtain a measure of the growth time in years or decades to double the growth.

Estimates of the growth constants for the technologies shown in this book are shown in Table 7.1 and compared with that of modern innovation growth such as cell phone use or Facebook enrollees. There appear to be a continuous advancement in the pace of innovation from the eighteenth to the twenty-first centuries. What is remarkable about this data is the fact that qualitatively, innovation growth has remained similar across technologies and across the centuries. As forecast in Alvin Toeffler's 1970s book (Toeffler 1970), *Future Shock*, the pace of change has quickened but the processes of change seem to have similar structures governed by the growth of social networks in the histories of innovation and invention.

7.2.1 Summary of Innovation Growth Curves

The innovation growth curves in Fig. 7.5 can be plotted on a logarithmic vertical scale and the approximate slope of the resulting curve is the growth constant in units of 1/decade. The time to double the number of events or nodes in the network in given by $T = Ln2/GrowthConstant$. Table 7.1, shows the estimated growth constants for the various technologies and sciences. It is clear that the difference between technologies in the modern age and those a century ago is the significant decrease in the time to double innovation information or product penetration into the marketplace.

Another way to view this historical data is to plot the time to double the innovation growth measures versus historical time, as shown in Fig. 7.6. One can plot network nodes, products sold, technology/scientific events, etc. Fig. 7.6 must be taken as a very rough plot, but the message is that there had been a continuous decrease in innovation growth doubling time across technologies and spanning several centuries.

The validity of this conjecture will have to wait further historical studies into other technologies. One might speculate on whether this has the structure of a power law in the sense that city populations are ranked by a power law as well as scientific citations studied by De Solla-Price (1963). This conjecture is in the same spirit as the work of George Zipf (1949) in his attempt the bring mathematics to the subject of sociology. It also follows the suggestions of Per Bak (1996) in the possibility

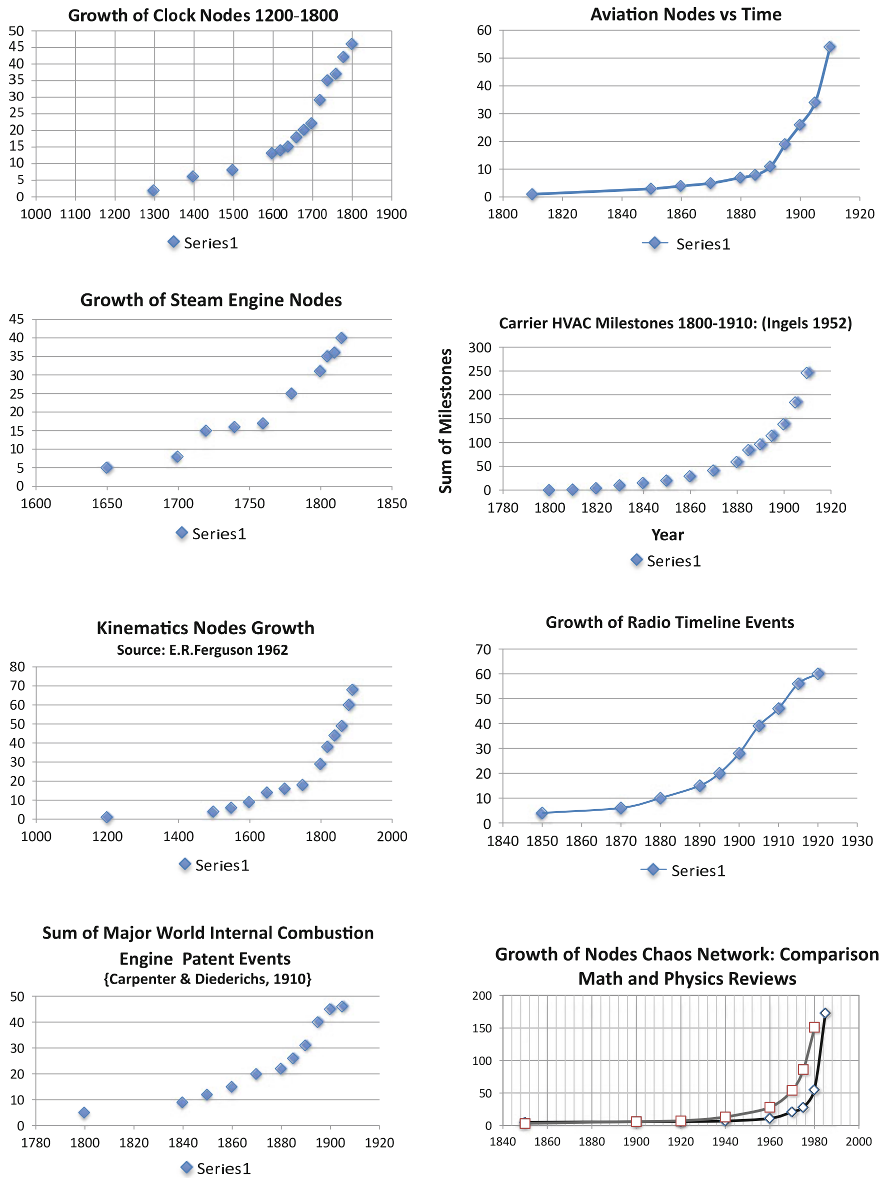

Fig. 7.5 Innovation growth *curves* for eight different technologies and sciences

of historical technical networks being governed by sand pile models and hence the natural occurrence of a power law behavior.

The reader might ask why the author did not follow up and see if other technologies would fit the model in Fig. 7.6. The simple answer is that the author did follow up

Table 7.1 Innovation exponential growth constants

Innovation type	Time frame	Exponential growth constant: 1/decade
Steam engine nodes	1650–1815	0.13
Steam engine growth (UK)	1710–1800	0.33
HVAC heat engineering nodes	1860–1910	0.50
Early aviation nodes	1880–1910	0.66
Internal combustion engine patents (US)	1880–1900	1.2
Wireless/Radio electronics nodes	1890–1920	0.65
Chaos theory nodes	1960–1985	1–1.8
Cell phone growth	1988–1998	3.2
Facebook users growth	2005–2010	9.2

since the original book was based on only four technical areas that grew into 10–12 technical and scientific studies. Although one can data-mine modern networks for thousands of data points as to usage, citations, network paths et cetera, historical networks require reading many books, reviews and other documents. Thus the task of exploring the power law conjecture of Fig. 7.6 must be seen as a work in progress.

7.2.1.1 Models for the Growth of Networks

The study of models for the growth of social networks is a large part of the study of modern network analysis. (See e.g. a recent textbook by Easley and Kleinberg 2010, ref in Chap. 1). There are problems of how a new idea propagates through an existing network, such as the adoption of some new crop seed in a community of farmers, or the creation of a larger network out of a set of clusters of smaller networks. Earlier we talked about the power-law property of networks in which a few nodes dominate the number of links as in the role of Google on the World-wide Web. Network textbooks call this the *rich-get-richer* effect. Attempts to understand this phenomenon began with Price's study of scientific paper citations in 1965 and was further developed by Barabasi and Albert in 1999 (see Newman (2003, ref in Chap. 1), for a discussion of network growth models). Price called this effect "*preferential attachment*" or the tendency for a new node to link up to the node in the network with the greatest number of links. This explanation may be good enough for an abstract mathematical model but historians might feel this is 'begging the question' as to why one technical network begins an exponential growth and another stalemates and declines.

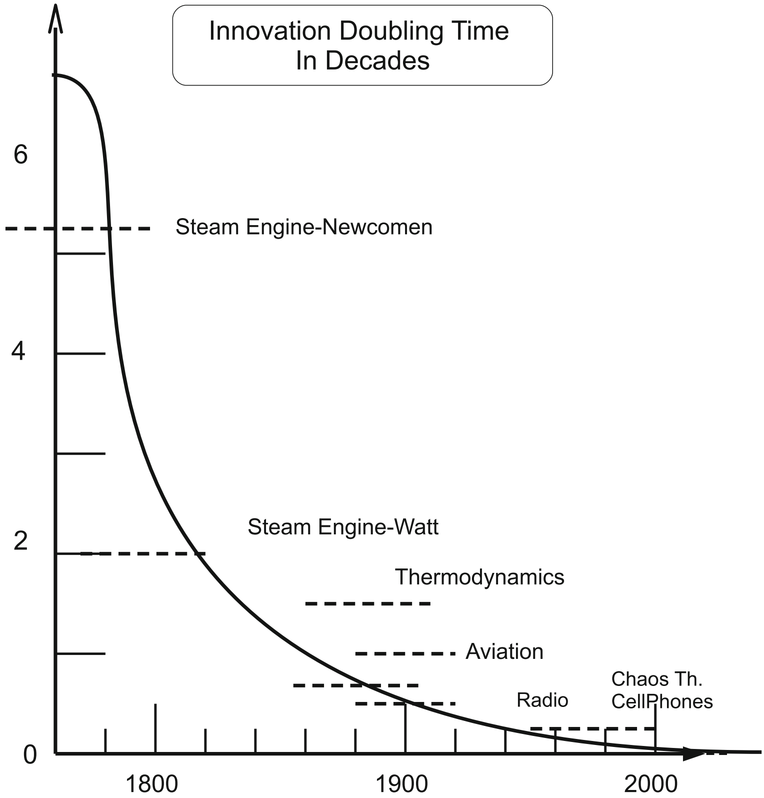

Fig. 7.6 Estimated decrease in the doubling time in decades for innovation across several technical and scientific fields based on the data in Fig. 7.5 and Table 7.1

7.3 Innovation Growth Models in Economics

Traditional economic theory was based on equilibrium models involving demand, supply and price as well as capital and labor. In the early twentieth century the Austrian-American economist Joseph Schumpeter [1883–1950] posited the idea that dynamic change was a better model and that one of the drivers of change was technological innovation. In Mokyr's book, *The Lever of Riches* (1990, ref in chap. 1), he uses the term *Schumpeterian growth*, defined as: *capitalist expansion driving from continuous, though fluctuating, technical change and innovation, financed by—credit*. In the wake of Schumpeter's ideas is a wealth of studies on innovation, especially the development of prediction models for innovation and diffusion of technical ideas and product into the marketplace. One recent collection of papers is *Economics of Innovation*, edited by Hall and Rosenberg (2010), with 29 articles in this two-volume work. A perusal of a university library section on economics of innovation will reveal

dozens of works and hundreds of research papers relating to technological innovation, invention, research and development (R&D) and diffusion of products.

What is the difference between economic studies of innovation and the history-based network theory of innovation discussed in this book? Economic studies generally focus on a shorter time scale: for example the time for corporate investment in innovation (R&D) to reap profits, or the time scale for a product to reach saturation. Historical studies of inventions often look at time scales of decades and centuries. A second difference between history-based and economic-based innovation studies is the nature of the questions asked. In history of technology we usually ask 'who, when and where' and in economics one asks 'how much'. Economic analysis often uses statistical data and probability models. In history of technology we are searching for specific connections, links, between each inventor node and other nodes in the network. There are exceptions of course. In a recent economic study from Germany, *Networks in the Innovation Process* (Graf 2006), the author draws network diagrams between industrial companies and research institutions around the German city of Jena [see Figs. 6.2 and 6.3, in Graf (2006)].

It is interesting to speculate on why economists seem to have a greater desire to understand the process of innovation than the engineering community who are often the genesis of technological invention. Inventors and innovators are those who look to the future and have traditionally shown little interest in how they create.

7.4 Fading Memory in Historical Innovation Networks

We have assumed that nodes promulgate across generations in the networks discussed in this book. This is tantamount to saying that knowledge generated by earlier nodes is of value to later persons and institutional nodes in the network. For example, Lenoir's experience in 1865 with a stationary internal combustion engine was relevant to the Otto-Langen engine of 1876, but was not likely useful for the design of the Daimler lightweight engine of 1896 in dirigibles. As the internal combustion engine network was growing, there were earlier nodes and links that were disappearing. We call this phenomenon *fading memory*. Like an old man who knows the latest football players but forgets the names of his old friends, innovation networks have both growing and dying branches. Another way of saying this is that the information commons for any given field can shrink as well as expand.

As an anecdote consider the field of electric batteries, the so-called voltaic cells of the nineteenth century. This is part of the field of electro-chemistry. Electric batteries were of importance to both chemistry and physics laboratories as well as the telegraph and telephone businesses of the late nineteenth century. To test our thesis that networks have fading memory we examined two popular textbooks on physics from 1899 and 1955. The French physics text by Professor Ganot was originally published in 1850 and translated into English by E. Atkinson through 15 editions. *University Physics*, by F.W. Sears and M.W. Zemansky, published in 1949 and 1955,

was a popular freshman text of its day. Each book has a section on electricity and electro-chemistry and batteries.

In Ganot (1899, Sect. 822), Voltaic cells are described in which two metals in a conducting liquid are used to generate an electric voltage. The voltaic battery is a series of voltaic cells based on copper and zinc in "acidulated water or brine". In the 1899 edition a set of improved batteries is described ; Wollaston's battery (Sect. 826), Daniell's battery (Sect. 829), Grove's battery (Sect. 830), Bunsen's battery (Sect. 831), Smee's battery (Sect. 832) and a number of "recent batteries by Marie Davy and Meidinger" (used for telegraph systems). These batteries used copper, zinc, carbon and platinum. No mention was made of lead-acid batteries used in today's automobiles.

In Sears and Zemansky (1955), there is also a section on galvanic cells or electrochemical batteries. Of the list of batteries in Ganot (1899), only the Daniell cell with zinc and copper is described in Sears and Zemansky. The lead-storage battery is described in detail (Sect. 30-11) as well as a Weston standard cell using mercury and cadmium from the Weston Electrical Instrument (Sect. 30-12). The names of Bunsen, Wollaston, Smee stc have disappeared from the electric battery information commons of 1955.

Another example using the same two physics texts of 1899 and 1955 is from the field of thermodynamics, relevant to the earlier case study in this chapter on air conditioning. Ganot (1899) has a 220 page section *On Heat* (Book VI) and Sears and Zemansky (1955) has a section "*Heat*" comprising Chaps. 15–20.

In a section on thermometers, Ganot lists mercury, alcohol and differential thermometers as well as Brequet's metallic thermometer and Sixes' thermometer. In Sears and Zemansky they describe 'liquid-in-glass, thermometers and mercury-in-glass thermometers as well as thermocouples, optical pyrometers and a constant-volume gas thermometer. Brequet and Sixes have disappeared in the thermometer network of 1955.

Yet another example from these two books are descriptions of calorimeters and the measurement of heat. Ganot (1899) lists the names of Favre, De la Roche, Regnault, Black and Bunsen calorimeters. These names have disappeared in the 1955 physics book of Sears and Zemansky. In Ganot there is a description of a steam engine or "Cornish engine" and no mention of the second law of thermodynamics. In 1955, Sears and Zemansky reduced steam engines to the Rankine cycle and internal combustion engines to Otto and Diesel cycles without any technical details of the machines' construction.

Perhaps we have belabored the point with the minutia of physics texts, but the message is that innovation networks die in parts as well as grow. When the old branches die faster than new nodes are added, the network dies completely as one can easily find in the debris of technology and science as in the fields of vacuum tube electronics and wave propagation in the ether. In this book we have focused only on growing innovation networks and leave the withering and death of such networks to another book.

7.5 The Role of the Genius-Hero in Innovation Networks

In our construction of invention and innovation networks in this book we have come across the following genius-innovator and hero-inventors:

James Watt: Steam engine;

Leonardo da Vinci: Construction of machines;

Franz Reuleaux: Kinematics of mechanisms;

John Harrison: Precision clocks;

Nikolas Otto: Four-cycle internal combustion engine;

Henry Ford: mass production of automobiles;

Montgolfier brothers: early balloon flight;

Wright brothers: controlled flight of airplane;

Gugliermo Marconi: Wireless telegraph;

Edwin Armstrong: modern radio circuits;

Balthazar van der Pol: mathematical analysis of electronic circuits;

Edward Lorenz: Modeling chaotic behavior of weather;

Willis H. Carrier: modern air conditioning technology.

What characterizes the hero-inventor/genius in the network study of innovation? In the traditional study of technology, often the hero is created by the person or the company that he/she founded. Sometimes the image or ‘branding’ is created by the media.

7.5.1 The Genius Theory of Innovation

In this book we have examined the networks attendant to these popular heroes of technology. Innovators and inventors have often been lionized by biographers and historians asleading the way to a new world of technology. We have tried however to

demonstrate that each of these men were surrounded by a cadre of equals, supporters and assistants who contributed essential ideas and talents to their success. It is likely that a detailed investigation of other paragons of invention such as Morse, Siemens, Edison, Bell, Madame Curie or even Steve Jobs would reveal similar results. Does this mean that the singular hero-inventor is dead?

In constructing social historical networks, we have found that the hero-inventor is often a node that generates a large number of incoming and outgoing links. It is in this sense that he or she is crowned a pioneer or leader in the field. It is not the one who is first with an innovation who is awarded the mantle of the hero-inventor, but the one who brings together both new and old knowledge, (generating incoming links) and inspires others to copy and improve his or her invention and innovation (generating outgoing links).

Thus we are not advocating a purely collective theory of innovation. The demise of the Soviet system provides evidence that discouragement of the creative talents of the individual and submission to the collective plan was not a good strategy for Soviet society. However the dual nature of the innovator and the social network is a dynamic we do not fully understand and historical analysis of earlier technologies may provide clues as to how it worked in the past and how it works today.

7.5.2 Epiphany Stories of the 'Genius-Hero'?

We have downplayed the importance of the epiphany story of the hero-inventor in order to argue for the role of the network within which the inventor was living and working. However the epiphany story is important in society as a motivational tool and a cultural marker of the importance of creating new ideas and products in the modern world. Our point however is that the recitation of these tales is no substitute for historical accuracy. Most modern corporations recognize that innovation success requires both creative individuals as well as a network of different talents. How to manage the tensions between the team and the genius in an organization is what business schools are for. The message in this book however is that the innovation network extends far beyond the corporate corridors. And as many organizations have discovered, so-called trade secrets sometimes are already imbedded in the knowledge commons beyond the corporation.

7.6 Role of the Media and the Knowledge Commons

In the construction of historical innovation networks we have included magazines and journals as nodes. In several examples we have seen the importance of books, magazines and scientific publications in providing links for the innovation network. The importance of books is seen in the 'theatre of machines' works published between the fifteenth and eighteenth centuries (see Chap. 2). In the nineteenth century peri-

odicals such as *Scientific American*, *Engineering* (London), *Cassier's Magazine* and *American Artisan* became nodes for the internal combustion engine and other technologies. They often presented extensive reports on international expositions where new machines were on display to generate sales and extend markets. Often new technologies create their own media as in the rise of the automobile with specialized magazines such as *Horseless Carriage*, or in aviation, *Aeronautical Journal* and in radio, *Electrical World*. Technically interested people regularly read these magazines in the nineteenth and twentieth centuries as we today scan the Internet for new ideas.

7.6.1 The Knowledge Commons

Though not treated as a separate node, in every field there accumulates a set of common knowledge as the field matures. This knowledge could take the form of general principles, empirical data, rules of thumb, misconceptions, recipes, formulas, topologies and geometries. General principles include Newton's laws of mechanics, data such as the strength of certain steels, recipes for the mixture ratios of copper and zinc, topologies such as the connections in an electrical circuit. This knowledge is passed around through handbooks, journals and magazines, expositions, artisan trial and error experience, technical meetings and personal correspondence. In the author's library there is an 1890 *Engineer's Sketch-Book* of mechanical movements, published by an engineer, Thomas W. Barber in London. This little book has 1936 sketches of mechanisms and machine details. Similar books appeared in the early twentieth century for electronic circuits. In the 1970's the Soviet Union published an English translation of Artobolevsky's handbook of kinematic mechanisms with over 5000 mechanisms.

The author has a 1930, 3rd edition of *Mark's Handbook* (Marks 1930), a mechanical engineering book first published in 1916 by Lionel Marks, a professor at Harvard and another graduate from the Cornell Sibley College of Mechanical Engineering at the time of Robert Thurston. In the 1930 edition, some of the contributors include, Willis Carrier, J.P. Den Hartog and Steven Timoshenko (see Chap. 6). Mark's Handbook is still published today. These treasuries of technical and scientific wisdom, published in many languages, are rarely mentioned or acknowledged by historians as having any role in the creation of technology. Yet as of 1930, there were 118,500 copies of *Mark's Handbook* sold.

In the study of political science and law there is a wider concept of '*the commons*' such as free public access to drinking water, parks, roads and school knowledge. Recently in a book *Common as Air*, writer Hyde (2010) discusses so-called 'intellectual property' and to what extend literary text, art and music belongs to the public commons. In this chapter we take a more limited definition of the *knowledge commons*. A pedestrian example is the knowledge one can find by spending time in an automotive garage while auto mechanics are fixing cars. The untrained person could very quickly discover what were the basic components of a car, where they were placed in different models and makes, what systems needed repair most often, what

lubricants and fuels were important in a modern car and how much things cost if they are to be replaced.

In the later years of the Cold War, the author was carrying out research on magnetic levitation of trains and had attended an international meeting in Japan at which some Soviet engineers were present. After the meeting an agent from an intelligence agency visited the author and asked if he had seen any important ideas at the meeting from the Soviet delegation. The agent was surprised when he learned he could have saved a trip since all the papers were published in a proceeding and were available to the public.

The knowledge commons most likely helped Charlie Taylor, the Wright brothers technician, build a lightweight internal combustion engine (12 hp, 220 pounds) for their 1903 flight (Crouch 1989). Many college glider clubs in the first decades of the twentieth were able to build human carrying gliders with shared technical details and published results from popular technical magazines. The knowledge commons was also a factor in creating the first electronic vacuum tube circuits that inspired the early amateur radio clubs.

7.7 Innovation Networks and the 'Paradigm Shift'

One reviewer of a preprint of this monograph asked if the network view of innovation had any relevance to Thomas Kuhn's famous book, *The Structure of Scientific Revolutions* (Kuhn 1962). Kuhn [1922–1996] was a physicist and philosopher of science. He described a process whereby 'normal' scientific thinking in a research community using classical problems or 'paradigms', eventually leads to conflicts with accepted ideas. This conflict produces a new, radical paradigm that triggers a scientific revolution. Two often cited examples are Einstein's theory of relativity and quantum physics. Kuhn's theory suggests that science proceeds in discontinuities, so-called "paradigm shifts" that appears to be at odds with the evolution model of science and technology put forward in this monograph.

Applied to technological innovation, the development of the internal combustion engine created a dramatic paradigm shift in the way machines were designed and enabled the creation of human carrying flying machines. The vacuum tube played a similar role in wireless communication and radio. In both cases the 'paradigm shift' was preceded by an exponential expansion of a social network. In our example of a network in scientific theory, the new ideas of nonlinear chaotic dynamics destroyed the 'normal' paradigm of a predictable Newtonian macro-science without quantum ideas. Here again the discoveries of Edward Lorenz in 1963, were proceeded by an earlier community of mathematicians, scientists and theoretical engineers. On the face of it, Kuhn's *paradigm shift theory* does not seem at odds with the idea of a social innovation network. His theory seems to embrace a community of scientists who both adopt a classic concept and eventually reject it.

The question of the role of the community or society in advancing science is a hotly debated topic in the philosophy of science and sociology. We have cited

the work of Derek De Solla-Price (1963) and Collins (1998) as two thinkers who examined the role of community and networks in science. In our work we have introduced the idea of a "knowledge commons" that contributes to the social network in producing innovations. However in advancing the ideas of social networks and knowledge commons we do not mean to suggest that scientific ideas depend on or are relative to community values or beliefs, as a few modern writers have put forward. In technology, there is nothing tentative about the lift on a curved airfoil or the resonance in a regenerative vacuum tube circuit. Aircraft are designed by engineers who come from dozens of different cultures, and airplanes don't fall from the sky when they fly over a cultural region that does not believe in modern physics. We are only discussing the *process* of innovation through networks and do not venture into the realm of cognitive science and creativity in the individual.

Finally as to the singular nature of Thomas Kuhn's theories of scientific process, the social network apparently played a part in his writings. An earlier scholar, Michael Polanyi [1891–1976] from the University of Manchester, is sometimes described as having influenced Kuhn's *Scientific Revolutions* book.

7.8 A New Approach to the Study of Innovation History

In this book we have posited an alternative approach to the historical narrative of invention and innovation based on networks and historical data modeling. Graphics, statistics and mathematics can't replace the traditional narrative history but are intended to complement the classical study of history of technology and science. For reference we summarize the methodology presented in this book.

Source Materials

The use of traditional biographical and historical studies of inventors and comprehensive treatises of technologies are of great value in constructing networks especially establishing the links between nodes.

Original documents from archives of inventors and scientists are very useful in establishing links between nodes especially those that are overlooked in biographies.

Web-based material can save time, especially Wikipedia, but should be heavily supplemented with traditional textural and archival material. Despite the promise of web-based libraries in the future, most textural material has not been scanned by Google, especially obscure technical treatises and documentation.

Graphical Analysis

Traditional timeline plots are useful in identifying principal nodes.

Star network diagrams centered around principal nodes are the next step.

The complex integration of star networks into a comprehensive network for an innovation field is a difficult task. It involves some aesthetics to make it readable. The lack of color in this book limited the information categories that could be used such as country of origin or principal or secondary nodes or enabling nodes. The vertical orientation of traditional books meant that time had to run from top to bottom whereas in an art setting, one would move time horizontally, typically from left to

right. In constructing the network online, one can also use CAD tools to construct 3D networks as is done for complex molecules such as DNA.

Integration of separate networks from different fields, such as electronics and nonlinear dynamics in Chap. 6 is a difficult task to show in a book form and might best be done in a web-based CAD environment.

Network Statistical Analysis

We have tried to use only the most elementary mathematical ideas from network theory and related fields. We introduced the *integrated knowledge growth function*, as a measure of the maturity of an innovation field and showed that some fields grow linearly and others have an exponential growth.

Different data bases have been used such as growth of product market penetration, number of patents, numbers of journals and publications and in the science world one can use numbers of citations as did de Solla Price in earlier studies of science.

The modern use of link-node statistics might be useful to establish hub nodes and small worlds and clusters of nodes. The problem with these tools is that for modern social networks such as the World-Wide Web or Facebook, statisticians have millions of data points to use whereas in the innovation history networks, studied in this book, one has only a few dozen nodes and perhaps a few hundred links. Nonetheless, humans are always making estimates from small samples. Here one must use judgment when interpreting small sample data.

One of the tools illustrated in Chaps. 1, 4, was the *influence matrix*, used for the steam engine and aviation networks. This technique could be further explored and perhaps codified to automatically calculate link-node statistics, shortest paths distributions, growth of links and nodes in time.

Mathematical Models for Innovation Growth

This is the weakest part of this book and only a few suggestions have been made in Chap. 1. Certainly the model types used in ecology and population dynamics might be used. Also chemical kinetics models for reacting atoms and molecules might suggest a path to predicting the growth of innovation and invention networks and links. Economic theorists have posited numerous models for innovation growth that may be relevant to historical studies.

Recent ideas from Complexity Theory such as *self-organized criticality*, are fascinating and may provide clues as to how human societies create new ideas, products and processes. What is missing is the mechanism for the micro and macro avalanches, or the slow and sudden growth modes of the links and nodes in the innovation network. Modern network analysis have also provided models for network growth based on probability measures. Economic models have sometimes used game theory approaches. But perhaps the historian of the future will have to look at cognitive science, to look inside the human brain, to see what motivates humans to create and embrace new ideas and inventions.

7.9 Hallmarks of Innovation

What is necessary for a culture to produce new ideas and technologies? In this book we have made the case for a societal role in innovation through historical networks. Historical and economic evidence has shown that there are a number of other societal conditions that must be present to incubate new ideas and technologies. Some of these conditions include the following.

(1) The society must have a tradition of creating new ideas and machines;
(2) There must exist a cadre of artisans and craftspeople with technical skills;
(3) There must exist a supply of capital to invest in new technology;
(4) There must exist a spirit of progress, that humankind is meant to improve and change its environment;
(5) The society must have a governmental structure that encourages change, new ideas and security for investors;
(6) There must exist individuals with a vision and motivation to change the status quo.

In the so-called middle ages, before the Renaissance, there was a growth of cities and guilds that produced skilled craftspeople. The Scholastics in the Church schools developed ideas of reason and progress as part of 'God's plan' for humanity. The merchant class developed and accumulated capital and a need to invest that capital. Also during the pre-Renaissance we saw trades emerge to create fantastic cathedrals and castles that required skills to organize workers and develop long term goals. Out of this milieu evolved the early machine age of Francesco di Giorgio and Leonardo da Vinci and the inexorable march to the industrial revolution of the nineteenth century age of machines and the twentieth century the age of electronics and information.

Yet as historians have painstakingly gathered evidence for this evolutionary model of scientific and technical progress, biographers have steadfastly maintained the myth of the genius inventor and innovator. The tension that arose between techno-historians and romantics in the eighteenth and nineteenth century continues to exist today.

Modern historians have tried to describe the last quarter century as a *Knowledge Revolution* in contrast to the Industrial Revolution based on machines. In pursuing the networks behind inventions in this book, we have used the idea of a *knowledge commons* active both before and during the Industrial Revolution, that helped evolve and spread the innovation concept and its attendant social networks. Humans have always organized themselves into networks to preserve and protect useful knowledge and the only difference between the present and past history is the amount of knowledge and the time scale in which it evolves.

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